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Diatomaceous Earth Filtration of 'Giardia' Cysts and Other Substances

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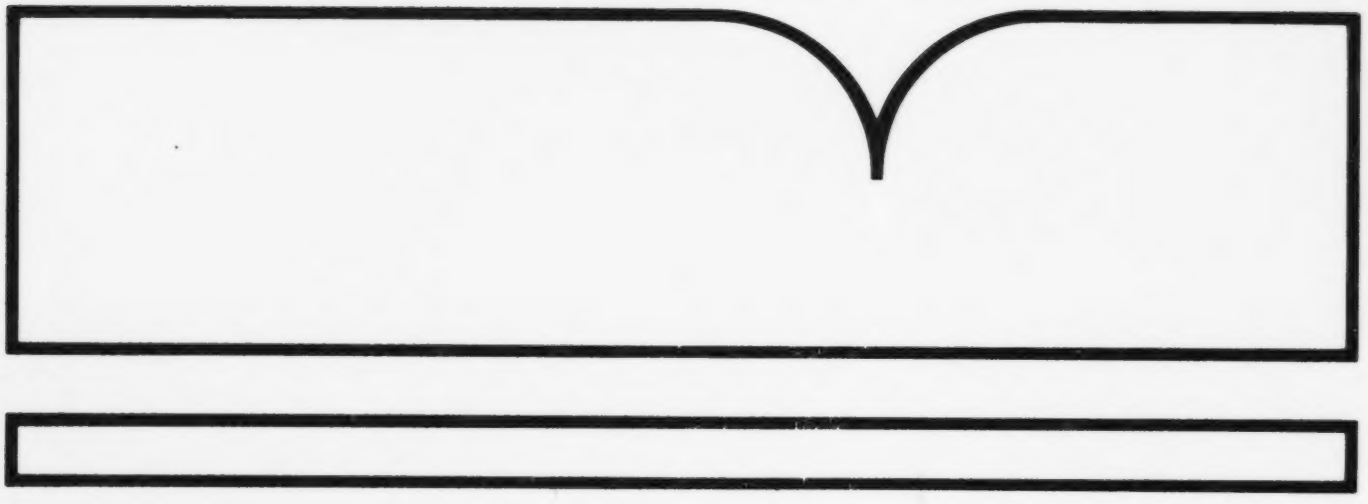

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16. ABSTRACT

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JOURNAL ARTICLE

Diatomaceous Earth Filtration of *Giardia* Cysts and Other Substances

Kelly P. Langé, William D. Bellamy, David W. Hendricks, and Gary S. Logsdon

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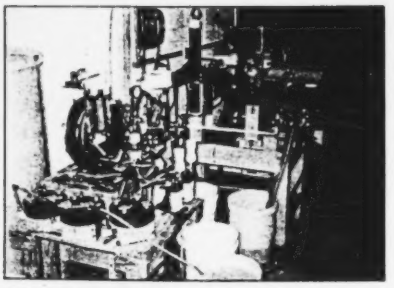

The main element of the pilot-plant setup used for this research is the filter, which comprises a 1-sq ft (0.09 m²) septum enclosed in a pressure housing.

Pilot-plant tests resulted in virtually 100 percent removals of *Giardia lamblia* cysts for both coarse and fine grades of diatomaceous earth over a wide range of conditions. Removals of turbidity and total coliform bacteria were functionally dependent on the grade of diatomaceous earth. Alum coating increased removal rates.

Reports of waterborne giardiasis outbreaks have increased in recent years,[1] stimulating researchers to determine water treatment technologies and operating conditions that could be used to effectively remove *Giardia* cysts. This article describes research conducted at the Engineering Research Center of Colorado State University (Ft. Collins) to ascertain the suitability of diatomaceous earth (DE) filtration for the removal of *Giardia* cysts. Removals of turbidity, total coliform bacteria, standard plate count bacteria, and particles were also determined. The following operating conditions were examined: DE grade (a commercial designation of particle size), hydraulic loading rate, influent concentrations of bacteria and *Giardia* cysts, head loss, run time, temperature, and the use of alum-coated DE. Water from Horsetooth Reservoir, adjacent to the Engineering Research Center, was used for most of the testing. This water has a low total dissolved solids concentration (e.g., 50 mg/L) and low bacteria and algae counts. Turbidity, however, ranges from 4–10 ntu, and is comprised of colloidal clays.

DE filtration process

The diatomaceous earth filtration process consists of three basic operations—precoating, filtering, and cleaning (Figure 1). Precoating is the application of a "precoat" filter cake (comprised of a 3- to 5-mm-thick layer of powder-size DE filter media) to a support membrane called a septum. The cake is applied by circulating flow from the precoat tank through the filter, depositing the slurried DE on the filter septum. Step 2, filtering, involves passing raw water combined with bodyfeed through the filter cake. Bodyfeed consists of measured amounts of a filter media slurry that is added to the raw water stream during filtration to maintain the filter cake permeability. The third step is cleaning, in which the filter cake is removed and discarded.

Operating parameters for DE filtration include grade, hydraulic loading rate, precoat thickness, bodyfeed concentration, terminal head loss, and run time. Under some circumstances, chemical coating of the diatomaceous earth may be used to improve removal effectiveness.

Generally, DE filtration is applicable for waters that do not contain high concentrations of sediments or algae, which are likely to cause "blinding" of the filter media. Blinding is a phenomenon that is manifested by inordinately rapid increases in head loss. As with any filtration process, pilot testing can delineate limitations.

Giardia lamblia. *Giardia lamblia*, which has only recently been identified as a pathogen, is of interest because of the prevalence of giardiasis. This disease is considered a serious problem in the mountainous regions of the United States, where the organism is endemic—residing in humans, dogs, and the wild animal population. *Giardia* cysts shed by dogs, humans, and wild animals (e.g., the beaver) are believed to be of the *Giardia lamblia* species.[2,3]

Figure 2 is a sketch of the *Giardia lamblia* trophozoite. It can reside in the intestines of a variety of warm-blooded animals. The cyst, shown in Figure 3, is the form which is shed and transmitted. Knight[4] states that an infected person may shed up to 900 million cysts per day. This is confirmed by data by Danciger and Lopez,[5] who examined 1000 stool samples from 15 infected children over a three-month period and found a range of 0.5 million to 7 million cysts per gram of feces. These large numbers of cysts, which may be present in infected animals as well, contribute to the transmission of *Giardia* to new hosts. A surface water supply source is, of course, a potential vehicle for the transmission of cysts, unless they are removed by treatment. The cyst form of the organism is hardy and may remain viable for a long period of time (e.g., two months), particularly in cold water. The findings of this study, however, indicate that a cyst may remain viable for only a matter of hours if the water temperature rises above approx-

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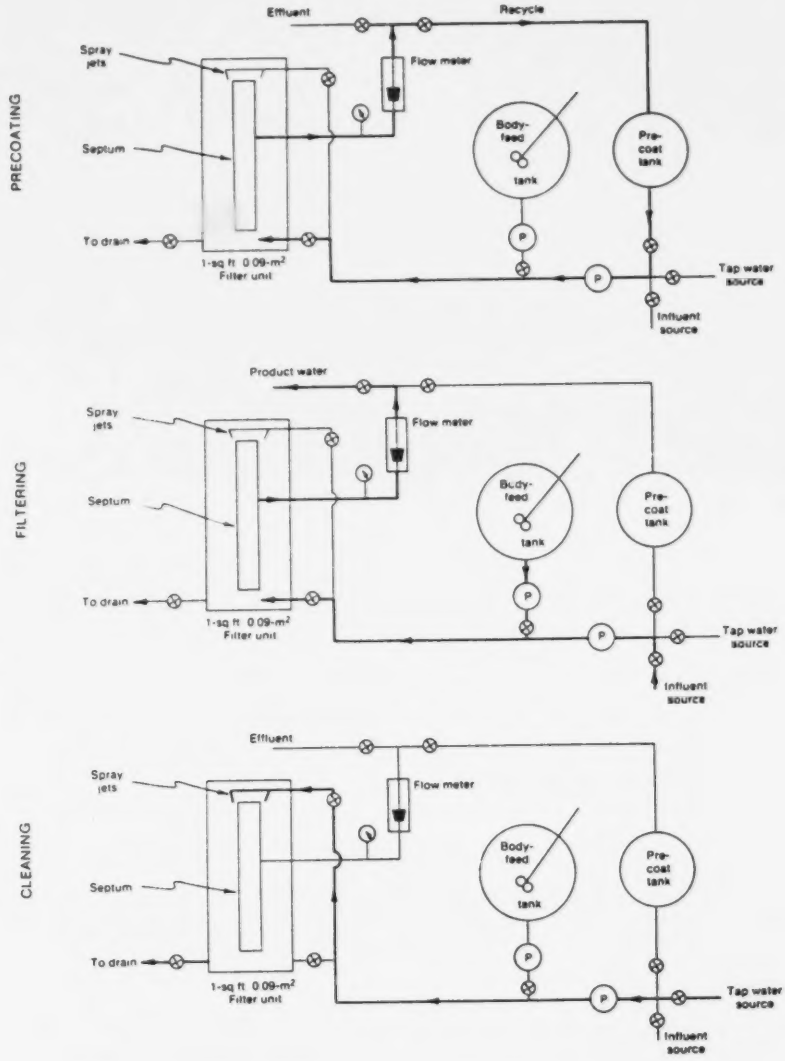

Figure 1. Flow schematic of the diatomaceous earth filtration steps

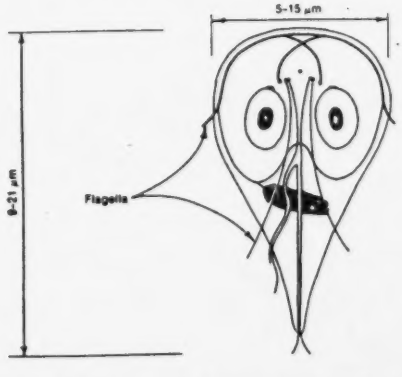

Figure 2. Trophozoite stage of *Giardia lamblia* (*after Jakubowski and Hoff*[1])

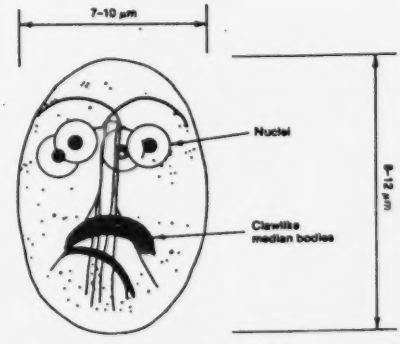

Figure 3. Cyst stage of *Giardia lamblia* (*after Jakubowski and Hoff*[1])

TABLE 1

Dependent variables measured in testing diatomaceous earth filtration performance

Giardia lamblia cysts
Total coliform bacteria
Standard plate count bacteria
Turbidity
Particle counts
Headloss

TABLE 2

Independent variables and ranges used in diatomaceous earth filtration testing program

Operating Conditions	Range
Grade of diatomaceous earth	A-G*
Run time	2, 5, and 16 h
Headloss	40 psi (276 kPa)
Hydraulic loading rate	1, 2, and 4 gpm/sq ft (2.44, 4.88, and 9.76 m/h)
Temperature	41°F, 59°F, ambient (52–66°F) 5°C, 15°C, ambient (11–19°C)
Influent coliform concentration	3800–380 000 coliforms/100 mL
Alum concentration	0–8 percent alum
Precoat thickness	0.20 lb/sq ft (0.093 kg/m²)
Bodyfeed concentration	25–400 mg/L
Bodyfeed to turbidity ratio	2.5–44.0

*Grades specified are products of Manville Corporation, Denver, Colo.: A—Filter-Cel, B—C-545, C—C-535, D—C-503, E—C-512, F—Super-Cel, G—Hyflo Super-Cel.

imately 64°F (18°C). Infection is caused by ingestion—an infective dose may be from 1 to 10 cysts,[6] and the incubation period from one to two weeks. Infected individuals may or may not have symptoms.

Past studies. Diatomaceous earth filtration was introduced in 1942 as a technology for water treatment by Cummins[7] and by Eisenbast and Morris.[8] It was adopted by the US Army for field use in 1944, after Black and Spaulding[9] showed it to be effective in removing *Endamoeba histolytica* cysts. Baumann and Babbit began studies in 1947 to examine the basic principles of the process.[10] Their studies encompassed filter septum design, bodyfeed effects on removals, and various factors affecting design and operation. Then, in the 1960s, the hydraulics of the process were delineated by LaFrenz and Baumann[11] and Baumann, Cleasby, and LaFrenz.[12] Hunter, Bell, and Henderson[13] described removals of coliform bacteria in terms of DE grade, feed concentration of coliform bacteria, bodyfeed concentration, and hydraulic loading rate. Brown, Malina, and Moore[14] achieved 98-percent virus removal when the filter cake was coated with ferric hydrate or polyelectrolytes. Then, at Duluth, Minn., alum coating was effective in removing asbestiform fibers.[15]

A recent study conducted by Logsdon et al[16] examined the effects of grade of diatomaceous earth and precoat thickness on removals of *Giardia muris* cysts and radioactive cyst-size beads. The results of their study showed that precoat thickness was more important than grade, and recommended a precoat thickness of 0.20 lb/sq ft (1.0 kg/m²). De Walle[17] confirmed these results using *Giardia lamblia* cysts.

Experiments

The experimental program utilized a diatomaceous earth pilot plant that had a 1-sq ft (0.09-m²) septum. The pilot plant was used primarily in the laboratory, but final confirmation testing was conducted in the field.

Testing program. The objective of the experimental program was to evaluate the removal effectiveness of DE filtration for the dependent variables listed in Table 1 as a function of the independent variables (i.e., the operating conditions) listed in Table 2. This was done by changing a given independent variable over a range of magnitudes and observing the effect on the filter's performance, i.e., the dependent variables. Table 2 also shows the range of testing for each independent variable.

The operating conditions of interest included: DE grade, hydraulic loading rate, temperature, raw water concentrations of coliform bacteria and *Giardia* cysts, and alum-coating of the diatomaceous earth. Tests were terminated either at the predetermined head loss across the septum (40 psi [276 kPa]) or after a given period of time. The precoat application was established at 0.2 lb/sq ft (1 kg/m²) for all tests as recommended by Logsdon et al.[16] The bodyfeed concentration was established,[15] i.e., successive concentrations of bodyfeed were tested until a linear head loss versus time relationship was ascertained.

Pilot plant. The pilot-plant setup used for this research was modified from a design used by the Manville Corporation. Figure 4 is a schematic of the pilot plant. The main element of the system is the filter, which comprises a 1-sq ft (0.09-m²) septum enclosed in a pressure housing. The septum used in this work was a stainless steel wire mesh of 110 × 24 wires per sq in. Pumps, valves, and gauges were used to control and operate the system.

The operating sequences and flow patterns are depicted in Figure 1. The flow configurations for precoating, filtering, and cleaning are emphasized with darker lines.

Experimental procedures. *Giardia* testing began with the processing of *Giardia* cysts from samples of dog feces. The processing consisted of adding the infected feces to distilled water, straining the feces, and then counting the cysts in the fecal concentrate. The *Giardia* cyst analysis procedure was performed by C.P. Hibler, a pathologist at Colorado State University.

The *Giardia* concentrate, at a known concentration, was then added to a 1400-L filter feed tank. This tank was a modified milk cooler that could be maintained at 5°C to 15°C ±1°C. The filter feed tank was filled with Horsetooth Reservoir water, which was cooled prior to the addition of the cysts. Primary settled sewage was also added to increase the concentration of total coliform bacteria in the feed tank.

Testing then began with precoating, as indicated in Figure 1. After precoating, the recycle was continued for 10 min while 10 mg chlorine/L was added for disinfection. The chlorine was purged by operating the filtering mode for 30 min. Sampling started after the 30-min washout period.

Samples were obtained from the filter feed tank and from the effluent side of the filter for measurements of turbidity, particle counts, total coliform bacteria, standard plate count bacteria, and *Giardia* cysts. Grab samples were collected for all parameters except *Giardia* cysts. Other measurements included: elapsed time from beginning of run, head loss, hydraulic loading rate, and water temperature. Particle counting was done with a commercial particle counter* for 12 size ranges, but results reported here are for the 3 size ranges collectively between 6.35 and 12.70 μm. *Giardia* cysts are nominally 6–10 μm in size.

The *Giardia* cyst sampling technique utilized a 142-mm diameter polycarbonate membrane filter, with a 5-μm pore size, to remove and concentrate the cysts from the sampled water. After concentrating the sample, the membrane filter was washed, and the wash water was analyzed for cysts by microscopic counting. The sampling technique was

developed by Luchtel et al;[18] the counting technique, which involved further concentration by centrifuging, and microscopic examination, was developed by C.P. Hibler. The influent water in the filter feed tank and the DE effluent were both sampled for *Giardia* cysts in this manner. The influent sample volume ranged between 2 and 10 L, whereas the effluent sample volume ranged between 86 and 1741 L.

Field tests to verify laboratory findings were conducted in April and May 1983. The April test utilized raw water from the Cache La Poudre River near Fort Collins, Colo., and the May tests utilized water from Straight Creek and Laskey Creek at the Dillon, Colo., water treatment plant.

Leak testing. During the initial phases of experimentation it became apparent that there was a need to determine whether a leak was present in the filter septum or in its manifold. Thus a technique was developed to test for leaks. First the filter was precoated with 0.4 lb/sq ft (2 kg/m²) of the finest grade of diatomaceous earth† (designated as DE grade A in this article), which is capable of removing 100 percent of the applied coliform bacteria. Then the filter was operated at 1 gpm/sq ft (2.44 m/h) for 1 h with a high influent coliform concentration. If any coliforms were detected in the effluent, the equipment was assumed to have a mechanical problem that was causing a leak, and the problem was corrected. This technique was used as a quality control measure throughout the testing.

Results

The DE filtration process was found to be effective for the removal of *Giardia* cysts under virtually all operating conditions tested. No cysts were detected in the filter effluent when water treatment practices were simulated. On the other hand, the removal of bacteria, turbidity, and particles was functionally dependent on: (1) DE grade, (2) use of chemicals, (3) hydraulic loading rate, and (4) influent concentrations.

Process effectiveness. Table 3 gives the operating conditions and results for all test runs involving *Giardia* cysts. Laboratory test runs are indicated by numerical designations; field tests are indicated by "F" prefixes. The results show that *Giardia* cyst removals are uniformly 100 percent (qualified by detection limits) regardless of DE grade, filtration rate, temperature, duration of test, or influent concentration of *Giardia* cysts (if < 10 000 cysts/L). Only one breakthrough of cysts occurred—the influent cyst concentration was 33 600 cysts/L and pressure loss was excessive (50 psi [345 kPa]).

*Model TAII, Coulter Inc., Hialeah, Fla.
†Filter-Cel, Johns Manville, Denver, Colo.

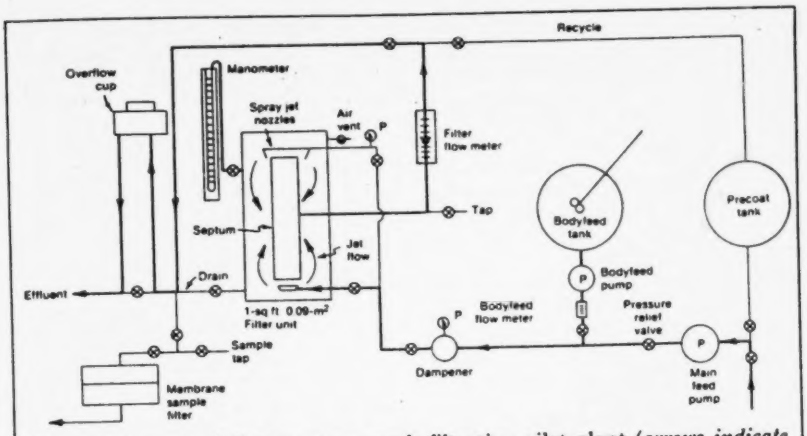

Figure 4. Layout of diatomaceous earth filtration pilot plant (*arrows indicate direction of flow for filtering mode of operation*)

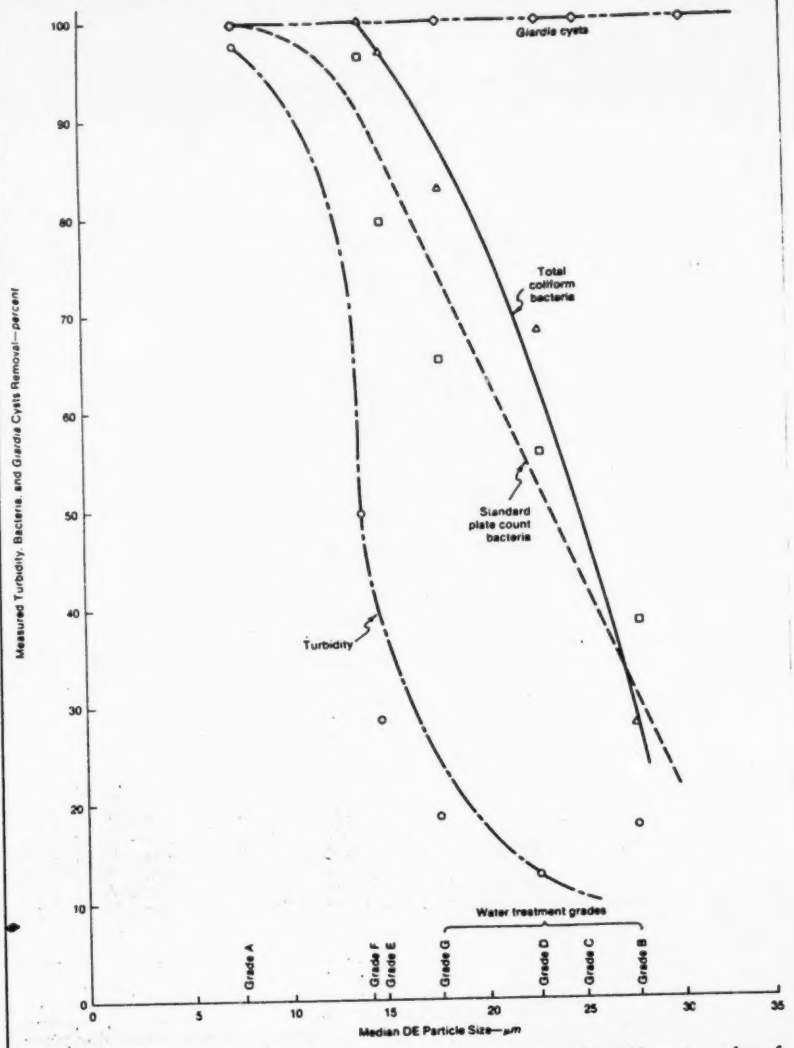

Figure 5. Removals of turbidity, bacteria, and *Giardia* cysts for different grades of diatomaceous earth (*†turbidity and bacteria data points represent averages for six test runs, 5-h duration;* Giardia *cyst data are averages for 32 test runs of various durations; mean particle size for different grades of diatomaceous earth are from* Johns Manville Celite Filter Aids for Maximum Clarity at Lowest Cost)

This concentration is well beyond what might be anticipated as a maximum ambient concentration, i.e., 100-500 cysts/L.[19]

Figure 5 illustrates the uniformly high removal of *Giardia* cysts as a horizontal line at 100-percent removal. Testing was done only for the water treatment grades of DE, since removal rates will be at least as high as those for the finer grades.

The grade of DE was not a factor in cyst removal. This is true for grades B* and C,† even though they create a filter cake with median pore sizes of 17 and 13 μm, respectively, which are larger than *Giardia* cysts. Obviously, many pores were also smaller than the cyst size and cyst passage was blocked.

Removals of coliform bacteria, standard plate count bacteria, and turbidity are also shown in Figure 5. Removal of each of these parameters approached 100 percent for the finest DE grades and fell below 40 percent for the coarsest grades. Removals of total coliform and standard plate count bacteria will follow a similar trend regardless of the water source. Turbidity removal, however, will depend on the size of the particles comprising the turbidity; improved removal will result if the turbidity is comprised of larger particles.

Effects of operating conditions. Operating conditions examined include: DE grade, hydraulic loading rate, *Giardia* cyst concentration, bacteria concentration, temperature, duration of filtration run, and alum coating.

Grade. As previously discussed, Figure 5 depicts the influence of DE grade on removals of the parameters shown. Removals of *Giardia* cysts were 100 percent (qualified by detection limits) for all grades tested. Removals of turbidity, standard plate count bacteria, and total coliform bacteria were strongly influenced by grade.

Not shown is the effect of grade on removals of particles. Removals of particles in the 6.35-12.70 μm size range—the size range of *Giardia* cysts—were uniformly high at 87.4-94.4 percent for the water treatment grades, as shown in Figure 5. No correlation of particle removal to grade was observed.

Hydraulic loading rate. Figure 6 shows the effect of hydraulic loading on removals of particles, standard plate count bacteria, coliform bacteria, and turbidity. Although there is scatter in the data, they show trends of declining percent removals with increasing hydraulic loading rate. Percent removals of total coliform bacteria were affected the most, standard plate count bacteria declined nominally, whereas particles and turbidity were affected only moderately. The fine clays comprising most of the raw water turbidity passed readily through grades B and D‡ at all the

*C-545, Johns Manville, Denver, Colo.
†C-535, Johns Manville, Denver, Colo.
‡C-503, Johns Manville, Denver, Colo.

TABLE 3

Giardia *cyst counts for diatomaceous earth filtration tests**

Identification			Conditions							
			Filtration Rate		Temperature		Duration of Test	Influent *Giardia*‡ Cyst Concentration		Effluent Volume Sampled
Date	Run Number	DE Grade†	*gpm/sq ft*	*m/h*	*°F*	*°C*	*min*	Added to Feed Tank *cysts/L*	Detected in Feed Tank *cysts/L*	*L*
7/14/82	13	B	1	2.44	41	5	90	100	27.7	103
7/26/82	18	B	1	2.44	55	13	90	100	50.5	86
7/27/82	20	B	1	2.44	41	5	90	500	229.0	94
7/30/82	28	B	1	2.44	41	5	340	770	75.0	633
9/30/82	42	B	1	2.44	55	13	145	10 000§§		549
10/5/82	43	B	1	2.44	59	15	150	5 460§§		568
10/12/82	45	B	1	2.44	57	14	260	8 850§§		984
8/26/82	41	B	1	2.44	54	12	55	3.36×10^4		208
11/18/82	49	B	1	2.44	51	10.5	980	2 467		1741
7/14/82	14	B	2	4.88	41	5	90	100	44.4	106
7/26/82	19	B	2	4.88	55	13	90	100	65.9	94
7/27/82	21	B	2	4.88	41	5	90	500	330.0	93
7/26/82	17	B	4	9.76	41	5	90	100	47.0	96
7/28/82	26	B	4	9.76	41	5	90	500	31.5	95
7/16/82	15	C	1	2.44	41	5	90	100	45.5	104
7/16/82	16	C	2	4.88	41	5	90	100	45.5	97
7/13/82	11	D	1	2.44	41	5	90	100	76.4	102
7/28/82	25	D	1	2.44	41	5	90	500	127.0	114
10/7/82	44	D	1	2.44	59	15	275	5 460		1041
7/13/82	12	D	2	4.88	41	5	90	100	40.0	104
7/27/82	22	D	2	4.88	55	13	90	100	59.0	95
7/28/82	24	D	2	4.88	41	5	90	500	127.0	88
7/28/82	27	D	4	9.76	55	13	90	100	33.0	114
7/12/82	9	G	1	2.44	41	5	90	100	41.4	101
7/12/82	10	G	2	4.88	41	5	90	100	27.2	106
10/12/82	45	B†††	2	4.88	57	14	40	8 850§§		151
4/17/83	F1	B	1	2.44	50	10	145	3 950		378
5/5/83	F3	B	1	2.44	38	3.5	105	1 000	229	227
5/6/83	F4	B	4	9.76	38	3.5	75	500	312	170
5/6/83	F5	B	2	4.88	38	3.5	90	1 000	740	248
5/6/83	F6	B	1	2.44	38	3.5	65	7 400	2248	132

*Note: All *Giardia* cyst analyses were conducted by the micropipette technique.
†B—C-545, C—C-535, D—C-503, G—Hyflo Super-Cel
‡The added influent concentration is the number of cysts contained in the feed tank, determined by analyzing the cyst concentration in a concentrated suspension of feces and adding this concentrate to a known volume of water in the feed tank. The detected influent concentration was obtained by sampling and analysis of the influent water from the feed tank.
§Membrane filter sampling efficiency = 100 (Influent cyst concentration detected in feed water) / (Influent cyst concentration added to feed water)
**Cyst detection limit = (20 Cysts/number of micropipette aliquots) / [(Membrane filter sampling efficiency) (Effluent volume sampled)]. The "20 cysts" is a multiplication factor inherent in the micropipette analysis technique.

hydraulic loading rates. Hydraulic loading rate had no detectible influence on the removal of *Giardia* cysts since all but one test resulted in complete removal of the influent cysts. The cysts are larger than some of the pores in the filter cake, which vary statistically, so they will be blocked by some pores as they are convected by the flow within the cake.

Influent concentrations. There was no discernible relationship between the *Giardia* cyst influent concentration and cyst removal. Influent cyst concentrations ranged from 500 to 10 000 cysts/L; one test run yielded 33 600 cysts/L. Only for the latter case were cysts detected in the effluent stream. This indicates that *Giardia* removal for expected ambient influent concentrations will be virtually 100 percent.

Figure 7 shows the effect of influent total coliform concentrations on the percent removals of total coliform bacteria for different DE grades.

The hydraulic loading rate was 1 gpm/sq ft (2.44 m/h) for all tests. Influent concentration had a stronger influence on removal for the water treatment grades than for the finer grades, which is reasonable since finer grades can completely strain coliform bacteria.

For the waters tested there was not sufficient variation in turbidity to determine whether there was a relationship between influent level and removal. For the laboratory tests conducted with Horsetooth Reservoir water, the influent turbidity levels ranged only between 4.5 and 5.4 ntu.

Most of the turbidity in Horsetooth water was caused by particles smaller than 1 μm. Consequently, a 1-ntu turbidity standard could be attained only with the smallest DE grade or by using alum-coated DE. Removal of coliform bacteria was higher, however, since they are about 0.5 μm × 2 μm in size, larger than much of the turbidity. The size of particles found in Horsetooth Reservoir are not necessarily characteristic of all waters, because many sources have been treated without chemicals to a 1-ntu standard with water treatment grades of diatomaceous earth.

Temperature. There were no discernible temperature effects for any of the parameters measured. Because the removal process in diatomaceous earth filtration is physical, slightly poorer removals might be expected at lower temperatures, because shear forces are higher. This possible effect was not observable, however, since changes in removal caused by variations in influent concentration and flow rate were significant and masked any temperature effects.

Duration of filtration run. The length of run time had no discernible effect on removal of *Giardia* cysts, particles, and turbidity. Figure 8 shows, however, that as the length of the filtration run increases, the total coliform removal decreases. The effect is stronger for the coarser grades. A similar trend was

TABLE 3

Giardia *cyst counts for diatomaceous earth filtration tests* (continued)*

Results				
Number of Cysts in Analysis of Effluent Sample	Membrane Filter Sampling Efficiency§ *percent*	Cyst Detection Limit** *cysts/L*	Effluent *Giardia* Concentration Corrected for Sampling Efficiency†† *cysts/L*	*Giardia* Cyst Removal‡‡ *percent*
0	27.7	0.701	<0.701	>99.299
0	50.5	0.461	<0.461	>99.539
0	45.8	0.465	<0.465	>99.907
0	9.7	0.326	<0.326	>99.958
0	32.5***	0.112	<0.112	>99.998
0	32.5***	0.108	<0.108	>99.998
0	32.5***	0.063	<0.063	>99.999
1700	32.5***	0.296	25.148	99.925
0	32.5***	0.0004	<0.0004	>99.999
0	44.4	0.425	<0.425	>99.575
0	65.9	0.323	<0.323	>99.677
0	66.0	0.326	<0.326	>99.935
0	47.0	0.443	<0.443	>99.557
0	6.3	3.342	<3.342	>99.332
0	45.5	0.423	<0.423	>99.577
0	45.5	0.453	<0.453	>99.547
0	76.4	0.257	<0.257	>99.743
0	25.4	0.691	<0.691	>99.862
0	33.0***	0.058	<0.058	>99.998
0	40.0	0.481	<0.481	>99.519
0	59.0	0.357	<0.357	>99.643
0	25.4	0.895	<0.895	>99.821
0	33.0	0.532	<0.532	>99.468
0	41.4	0.478	<0.478	>99.522
0	27.2	0.694	<0.694	>99.306
0	32.5***	0.408	<0.408	>99.995
0	32.5	0.162	<0.162	>99.996
0	22.9	0.385	<0.385	>99.962
0	54.4	0.216	<0.216	>99.931
0	74.0	0.109	<0.109	>99.989
0	30.8	0.492	<0.492	>99.993

††Effluent *Giardia* cyst concentration corrected for sampling efficiency = (Number of cysts detected in effluent / [(Membrane filter sampling efficiency) (Effluent volume sampled)]; if zero cysts were detected, this value was taken as the detection limit.

‡‡*Giardia* cyst percent removal = 100 (Influent cyst concentration added to feed water − Effluent *Giardia* cyst concentration corrected for sampling efficiency) / (Influent cyst concentration added to feed water)

§§Cysts were added for the first hour, and the total effluent was sampled for the entire period.

***The influent cyst concentration was not determined after the cysts were added to the storage tank; sampling efficiency for these tests is taken as the average of all similar tests.

†††This test is a 40-min test performed at the end of test run 45. Test 45 was conducted at 1 gpm/sq ft (2.44 m/h) until the last 40 min, when the rate was increased to 2 gpm/sq ft (4.88 m/h).

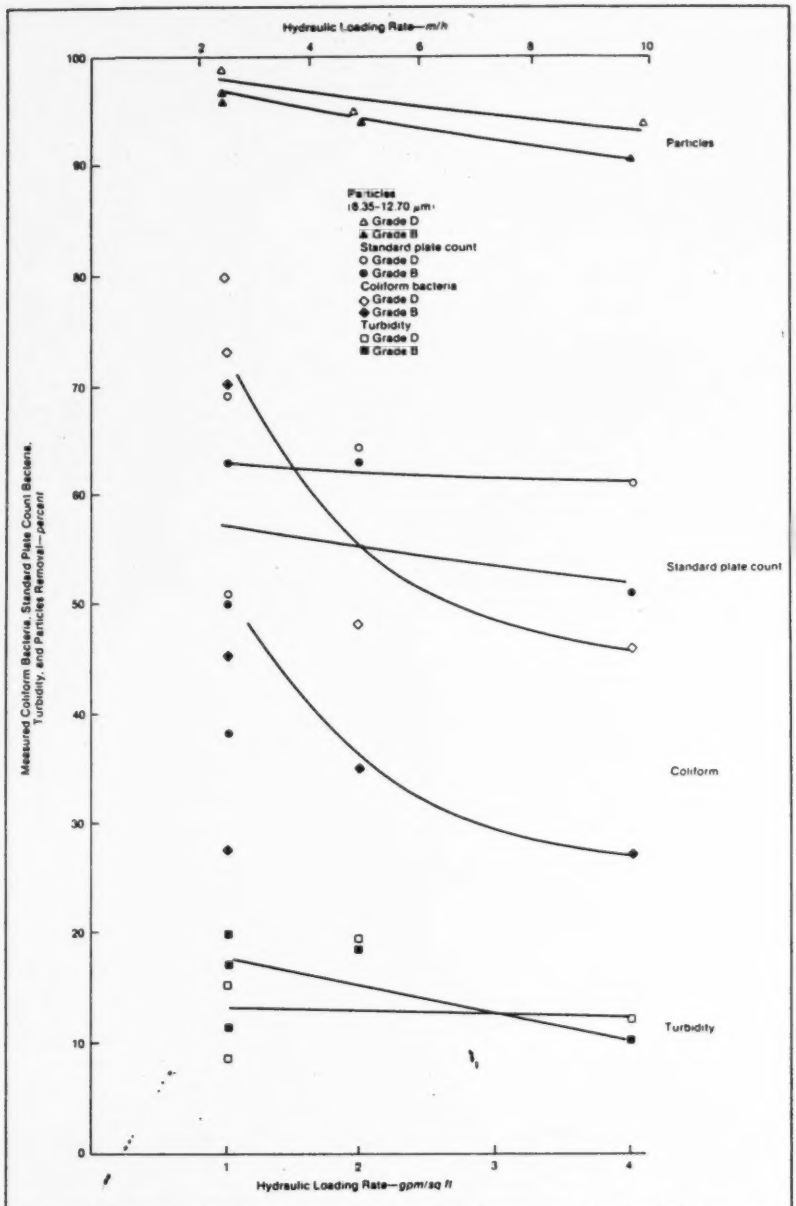

Figure 6. Hydraulic loading rate versus removal of particles, standard plate count, coliforms, and turbidity for diatomaceous earth grades B and D

shown for removals of standard plate count bacteria. These results were based on 5-h test runs, conducted to determine how filtration effectiveness changes with duration of filtration. Most of the filter test runs were operated for a shorter duration—i.e., long enough to collect research data, but not to terminal headloss.

Alum coating. Table 4 shows the improvement in average rates of total coliform bacteria, standard plate count bacteria, and turbidity removals, which resulted from the use of alum-coated diatomaceous earth. Coarse grades of DE were used, e.g., grades B and D, and both the precoat and bodyfeed were coated while in the slurry form. Removals of total coliform bacteria ranged from 96 to 99.9 percent with alum coating, compared with 30 to 70 percent without alum coating. Removals of standard plate count bacteria ranged from 79 to 99.5 percent with alum coating, compared with 38 to 56 percent without alum coating. Turbidity removals ranged from 66 to 98.8 percent, compared with 11 to 17 percent without alum coating. These results demonstrate improved treatment when alum coating is used and show how DE filtration can be applied in otherwise marginal situations.

Not all water sources can be treated to a 1-ntu standard with the normal water treatment grades of diatomaceous earth. To obtain a 1-ntu effluent for these cases, it is necessary to weigh the advantages of alum coating versus using a finer DE grade. Both techniques will reach the desired goal, but only pilot-plant studies and economic considerations can determine which approach should be taken.

Differential pressure. The rate of increase in differential pressure across the filter cake had a marked effect on effluent particle counts. Table 5 illustrates this by comparing particle counts for a high rate of pressure increase, 0.1 in. Hg/min (0.35 cm Hg/min), to a low rate, 0.02 in. Hg/min (0.06 cm Hg/min). At the high rate, there were more particles in the effluent (428/mL) than in the influent (47/mL). In contrast, for the low rate of differential pressure increase there was a substantial reduction in particles, from 7572/mL in the influent to 69/mL in the effluent. The increase in the particle concentration at the high rate of differential pressure increase is believed to have been caused by the collapse of DE particle bridges at the septum, resulting in their release through the septum. Microscopic examinations confirmed that diatomaceous earth was present in the filter effluent. Such filter cake attrition can account for a substantial portion of the effluent particles in the 2-12-μm size range.

Field testing

Field testing data are included in Table 3 and are designated with an "F" prefix for the run number. The tests were conducted with water from the Cache La Poudre River and raw water at the Dillon water treatment plant, respectively. Turbidity conditions were about 4 ntu for tests conducted Apr. 17, 1983, at the Cache La Poudre River and about 0.6 ntu for the May 1983 tests at Dillon. Despite these different water sources, no *Giardia* cysts were detected in any of the filtered water samples. Removals of turbidity, total coliform bacteria, and total plate count bacteria were consistent with laboratory results. These tests confirmed the laboratory results under field conditions.

Conclusions

- Diatomaceous earth filtration is virtually 100 percent effective in *Giardia* cyst removal for all DE grades over a wide range of conditions.
- Grade is the most important factor in the removal of bacteria and turbidity. When comparing removals between coarse and fine grades, turbidity removal was improved from 17 to 98 percent, coliform bacteria from 28 to 99.9 percent, and standard plate count bacteria from 38 to 99.8 percent.

- Increasing the hydraulic loading rate causes a decrease in the removals of bacteria, particles, and turbidity for the water treatment grades of diatomaceous earth. The effect was strongest for coliform bacteria and weakest for turbidity. Hydraulic loading rate showed no effect on removal of *Giardia* cysts.
- The effectiveness of DE filtration was not influenced by temperature, as determined by testing over a temperature range of 38 to 59°F (3.5 to 15°C).
- Percent removals of bacteria decreased with increased influent concentrations of bacteria, especially for coarser DE grades. A three-log increase in influent coliform concentration reduced removal from 77 to 39 percent for grade B, but for grade E,* a two-log increase in coliform concentration reduced removal from 96 to 92 percent.
- Percent bacteria removal decreased slightly with increasing filtration time. Removal decreased from 87 to 79 percent in 5.5 h for grade D and from >99.98 to 99.92 percent for grade F.†
- Alum-coated DE significantly improved removals of turbidity and bacteria. Compared with DE filtration with no alum, the use of alum coating increased removals from 17 to 99 percent for turbidity, from 30 to 96 percent for total coliform bacteria, and from 56 to 99.5 percent for standard plate count bacteria.
- Increased removal of turbidity and bacteria can be accomplished either by chemically coating the DE or by using a finer grade.
- Field testing with two different raw waters gave the same results as laboratory tests.
- Pilot plant testing should be done prior to any application. The applicability, design criteria, and operating conditions cannot be determined without pilot studies.
- A DE filtration system should be periodically checked for leaks by applying infusorial earth and then filtering a coliform contaminated water.

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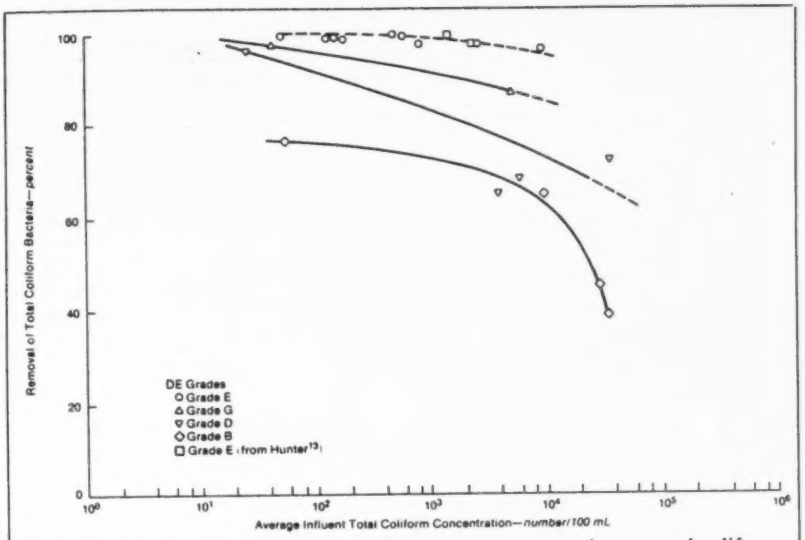

Figure 7. Relationship of influent total coliform concentration to total coliform removal

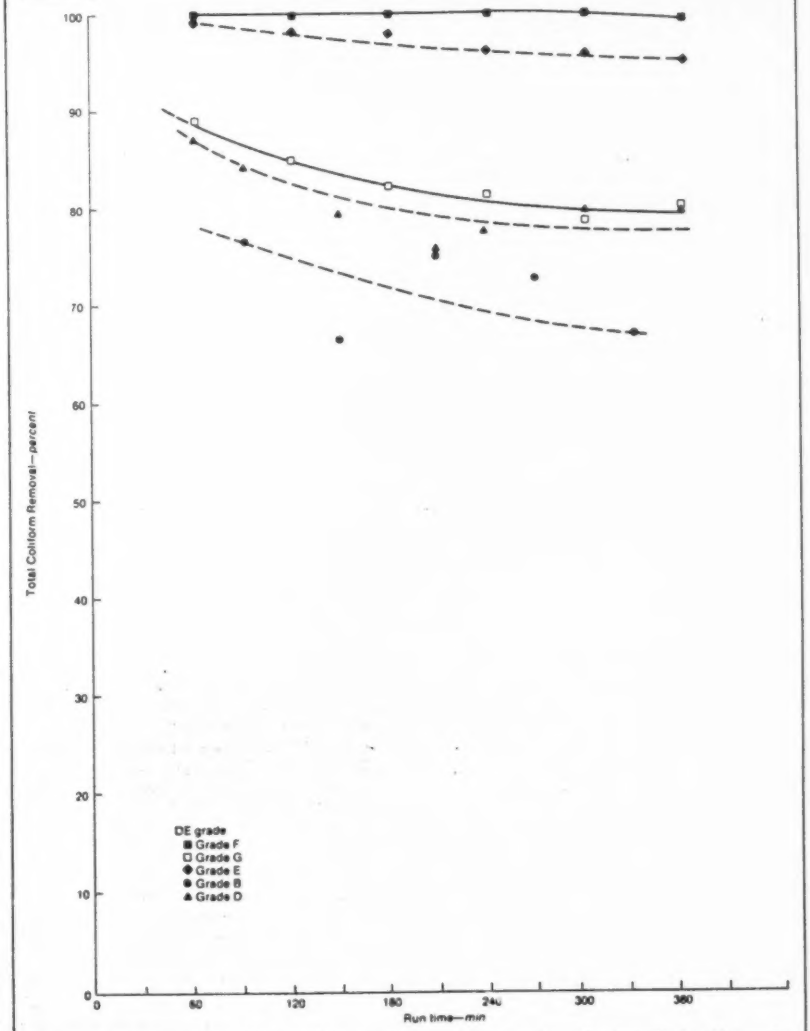

Figure 8. Removal of total coliform bacteria with run time (*hydraulic loading rate was 1 gpm/sq ft [2.44 m/h] for all tests*)

*C-512, Johns Manville, Denver, Colo.
†Super-Cel, Johns Manville, Denver, Colo.

TABLE 4

Removal percentages of total coliform bacteria, standard plate count bacteria, and turbidity for DE grades B and D coated at various alum concentrations*

Grade	Alum to DE Ratio† gm alum / gm DE	Body Feed Concentration mg/L	Average Influent Concentrations and Average Removals					
			Total Coliform		Standard Plate Count		Turbidity	
			Average Influent number/100 mL	Removal percent	Average Influent number/mL	Removal percent	Average Influent ntu	Removal percent
B	0.02	25					9.5	66.11
	0.04	25	3450	99.02	26 125	95.02	8.0	86.41
	0.04	25	3450	99.02	26 125	95.02	8.0	86.41
	0.05	25	5800	99.86	4 120	98.56	9.4	98.38
D	0.05	25‡	4975	98.01	750	79.31	9.5	79.06
	0.05	25	6950	99.56	2 278	93.25	9.5	94.41
	0.05	50	6150	96.33	18 750	99.57	9.8	98.61
	0.08	25	7100	99.83	27 200	99.52	11.0	98.80

*B—C-545, D—C-503

†Alum coating ratio is grams of alum as $Al_2SO_4 \cdot 14.3\ H_2O$ slurry per gram of diatomaceous earth in slurry.

‡Bodyfeed concentration was increased to 50 mg/L after 3 h of testing at 25 mg/L.

TABLE 5

*Particle analyses (size range 2.5 to 12.7 μm) for different rates of differential pressure increase across a diatomaceous earth filter**

Rate of Increase Differential Pressure		Influent Particle Concentration	Effluent Particle Concentration
in. Hg/min	cm Hg/min	Number/mL	Number/mL
0.1	0.35	47	428
0.02	0.06	7572	69

*DE grade F—Super-Cel

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